

# Recent Searches for Pulsars in Unidentified EGRET Error Boxes

M. ROBERTS

*Dept. of Physics, McGill Univ., Montréal, QC, Canada  
Center for Space Research, MIT, Cambridge, MA*

## ABSTRACT.

Pulsars discovered since the end of the *EGRET* mission coincident with unidentified high-energy  $\gamma$ -ray sources are prime targets for *AGILE*. Both general surveys and targeted observations have been successful in finding energetic young pulsars in the plane of the Galaxy. For the latter, hard X-ray imaging followed by deep radio searches of X-ray sources is a proven route. High-resolution Chandra X-ray imaging has discovered several asymmetric pulsar wind nebulae associated with apparently variable  $\gamma$ -ray sources along the Galactic plane. The unidentified sources at intermediate Galactic latitudes, with their much larger error boxes, make new X-ray studies impractical. A radio search of a number of these sources using the Parkes multibeam system has resulted in the detection of several new binary pulsar systems. Whether these are potential  $\gamma$ -ray emitters has yet to be determined.

## 1. Introduction

The periods of all known  $\gamma$ -ray pulsars were originally discovered at lower energy wavelengths. Although it has been shown that pulsations could have been discovered from the Crab, Vela, and Geminga pulsars from just the *EGRET* data without a priori knowledge of their pulse periods (Jones 1999), all detections of  $\gamma$ -ray pulsations were achieved by folding the data given an X-ray or radio ephemeris. While there is the hope that blind searches of *AGILE* and *GLAST* data may result in some pulsar detections, the tendency of energetic young pulsars to glitch and have timing noise and the planned default scanning mode of the *GLAST* mission will greatly complicate such searches. Current radio or X-ray ephemerides and precise positions allow any amount of data to be folded coherently without having to search through  $P - \dot{P}$  space. They also make unnecessary the restriction of searches to observations of a few months or less due to the large effective  $\ddot{P}$  from timing noise and worries about glitches. It is therefore highly desirable to detect potential  $\gamma$ -ray pulsars before the next generation of high energy  $\gamma$ -ray missions are launched.

The *EGRET* mission has left us a legacy of unidentified Galactic  $\gamma$ -ray sources at low and mid-Galactic latitudes, many of which will undoubtedly turn out to be pulsars. In recent years, several new young pulsars have been found coincident with unidentified *EGRET* sources. Some of these, such as the 69 ms PSR J1420–6048 in the Kookaburra (D'Amico et al. 2001), were discovered in the Parkes Multibeam Survey (Kramer et al. 2003). However, many young radio pulsars are too faint to be detected in general surveys. Fortunately, young pulsars often reveal themselves as X-ray point sources or through the X-ray or radio emission of an associated wind nebula. In fact, about a third of the known pulsar wind nebulae (PWN) are associated with known  $\gamma$ -ray pulsars or are coincident with unidentified *EGRET* sources.

## 2. Finding Potential $\gamma$ -ray pulsars

An unidentified  $\gamma$ -ray source can serve as a guide to lower energy searches, with the classic case being the discovery of the Geminga pulsar through its X-ray emission (Halpern and Holt, 1992). In general, a strategy of hard ( $> 2$  keV) X-ray imaging of a  $\gamma$ -ray error

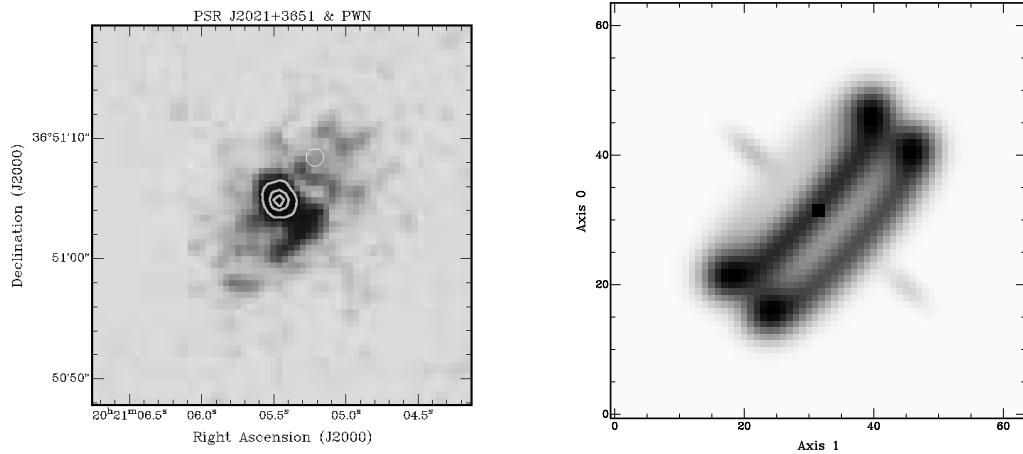


Fig. 1. Left: Chandra X-ray image of PSR J2021+3651. Right: Sample (not fit) model of torus plus jet for a specific geometry (courtesy C.-Y. Ng).

box followed by radio imaging and deep radio pulse searches has proven successful. This method has resulted in the discovery of at least six pulsar wind nebula, three of which contain radio pulsars which were discovered subsequently (Halpern et al. 2001, Roberts et al. 1999, Roberts et al. 2002).

The case of PSR J2021+3651 is an illustrative example. COS B first detected a high-energy  $\gamma$ -ray source in this part of the Cygnus region. Shallow radio pulse searches (Nice and Sayer 1997), soft X-ray imaging and hard X-ray imaging using an early *EGRET* position failed to discover any sources of note (Mukherjee et al. 2000). A 2-10 keV *ASCA* image based on a revised position derived from  $> 1$  GeV *EGRET* data discovered the compact hard X-ray source AX J2021+3651. The X-ray localization allowed a deep search for radio pulsations using the Arecibo telescope, resulting in the discovery of the young, energetic (but radio faint  $S_{20cm} \sim 0.1$  mJy) 104 ms pulsar PSR J2021+3651 (Roberts et al. 2002). A follow up Chandra observation showed this to be embedded in a compact X-ray pulsar wind nebula with the standard torus and jet morphology (Hessels et al. 2003).

Imaging of these type of nebulae may be important for constraining models of high-energy emission. The orientation of the X-ray jets, presumably aligned with the pulsar's spin axis, and that of the torus, presumably aligned with the equator, tell us the viewing angle (Ng and Romani 2003). Combined with the polarization sweep (Radhakrishnan and Cooke 1969) and possibly the pulse morphology, the magnetic inclination angle can also be strongly constrained. Since models of high-energy pulsed emission generally depend on only the spin rate, magnetic field, and pulsar geometry, these observations should allow theorists to predict what *AGILE* and *GLAST* should see from these newly discovered pulsars.

### Energetic Pulsars Recently Discovered in EGRET Error Boxes

Pulsar	$\log \dot{E}$ erg/s	$\log B$ G	D <sup>a</sup> kpc	Ref.
J2229+6114	37.4	12.3	3.97	Halpern et al. 2001
J1420–6048	37.0	12.4	5.63	D'Amico et al. 2001
J2021+3651	36.5	12.5	12.4	Roberts et al. 2002
J1016–5857	36.4	12.5	8.00	Camilo et al 2001
J1837–0604	36.3	12.3	6.4	D'Amico et al. 2001

<sup>a</sup> Dispersion measure distances using the NE2001 model of Cordes and Lazio.

### 3. Pulsar Wind Nebula Associated with Variable $\gamma$ -ray Sources

The pulsed emission from the known  $\gamma$ -ray pulsars is very steady on timescales much longer than the pulse period. However, there is good evidence of at least one class of variable Galactic  $\gamma$ -ray sources (McLaughlin et al. 1996, Nolan et al. 2003). *ASCA* 2–10 keV images have been made of nearly all of the sources which are bright above 1 GeV (Roberts, Romani and Kawai 2001). The brightest non-thermal source in the error boxes of the four Galactic GeV sources showing the most evidence of variability appears extended even with the low resolution of the *ASCA* telescopes, suggesting they might all be pulsar wind nebulae. Indeed, one of them is the known PWN around PSR B1853+01 in the SNR W44 which has a trailing plume morphology in radio and X-rays (Frail et al. 1996, Petre et al. 2003). The other three sources have now been imaged in radio and with high resolution X-ray telescopes. Two of them have radio nebulae with the spectral and polarization characteristics of PWN, both with bow-shock morphologies (Roberts et al. 1999, Braje et al. 2002). In X-rays, Chandra imaging of all four sources show a point source with a trailing jet type morphology.

In the table below, we list these four sources with their  $V_{12}$  and  $\delta$  values from Nolan et al. 2003.  $10^{-V_{12}}$  is the likelihood that  $\delta < 0.12$ , where  $\delta \equiv \sigma/\mu$  (standard deviation over mean) is a measure of how variable a source is with 0.12 being a conservative estimate of the systematic variability of *EGRET* data. The typical time scale of this variability is a few months, and the amplitude of the variability is on the order of the mean flux. Chandra observations of hard X-ray variability in the bright PWN around the Crab, Vela, and PSR J1811–1925 in SNR G11.2–0.3 have established the dynamic nature of the emission from jet-like structures coming from pulsars (Hester et al. 2002, Pavlov et al. 2003, Roberts et al. 2003). Whether through beaming, magnetic field enhancements, or some other mechanism this emission can extend up to  $\gamma$ -ray energies is an open question.

### PWN in Error Boxes of Variable *EGRET* Sources

PWN	$\delta^a$	$V_{12}^b$	Ref.
Rabbit	$1.03^{+0.80}_{-0.66}$	1.59	Roberts et al. 1999
GeV J1809–2327	$0.71^{+0.42}_{-0.25}$	3.93	Braje et al. 2002
GeV J1825–1310	$0.88^{+0.57}_{-0.38}$	3.22	Roberts et al. 2001
PSR B1853+01	$0.71^{+0.82}_{-0.43}$	1.57	Petre et al. 2003

<sup>a</sup> Variability magnitude parameter from Nolan et al. (2003) with 68% confidence region for  $\delta \equiv \sigma/\mu$ ; <sup>b</sup> Variability determination statistic from Nolan et al. (2003).  $V_{12} = 1.3$  rejects constant hypothesis at 95% confidence level.

#### 4. A Radio Survey for Pulsars in Mid-Latitude EGRET Error Boxes

While the exact nature of most of the low Galactic latitude sources remains a mystery, in many cases plausible low-energy counterparts have been identified which can be confirmed by *AGILE* and/or *GLAST*. At latitudes  $|b| > 10^\circ$ , only one or two non-Blazar candidate counterparts have been suggested for unidentified sources (eg. a neutron star for the singular high-latitude GeV source 3EG J1835+5921, Mirabal et al. 2000). At mid-Galactic latitudes, there is at least one population of sources associated with the Galaxy which on average are weaker and have a significantly steeper spectrum than the unidentified sources along the Galactic plane (Hartman et al. 1999). Spatially, these may coincide with the Gould Belt, a local region of recent star formation, and/or the Galactic Halo (Grenier 2002 and elsewhere in these proceedings). Due to their proximity ( $d \sim 50 - 300$  pc), pulsars born in the Gould belt might appear  $\gamma$ -ray bright for longer periods of time and at larger off-axis angles than pulsars at typical Galactic distances of a few kpc (Harding et al. 2003). It is also possible that millisecond pulsars, whose Galactic scale height is much greater than that of young pulsars, could form a halo population of  $\gamma$ -ray pulsars with a different typical spectra than the young pulsars (Kuiper et al. 2000, Romani 2001).

Practically speaking, these sources will be difficult to identify. The typical 95% confidence *EGRET* error contour for these sources is  $\sim 1.5^\circ$  across, much larger than the typically  $< 1^\circ$  error boxes of the harder, low-latitude sources. The steep spectra of these sources mean that the great improvements in resolution projected for *GLAST*, largely due to its good sensitivity to photons above 1 GeV which have relatively small PSFs, may not be nearly so great for these sources. In fact, for the softest sources, *AGILE* may do nearly as good a job at localization as *GLAST*. Since there are no wide-field imaging X-ray telescopes operating in the 2-10 keV range, the strategy outlined above is impractical with the current error boxes. A prime goal of *AGILE* with respect to these sources is to localize them to better than  $30'$  so as to be observable with a single X-ray pointing by XMM.

Radio pulse searches of the error boxes are practical and highly desirable. If there is a significant population of millisecond  $\gamma$ -ray pulsars, a priori knowledge of a current timing ephemeris will be absolutely crucial to their detection as  $\gamma$ -ray sources. The large search space in frequency and frequency derivative required to detect millisecond pulsations in blind searches of *AGILE* or *GLAST* data will be computationally prohibitive and not very sensitive. In addition, the tendency of millisecond pulsars to be found in binary systems further complicates searches. Even with slower, isolated pulsars, a radio ephemeris would greatly facilitate the search for  $\gamma$ -ray pulses.

The Parkes Multibeam system makes deep radio pulse searches of large regions of the sky at 20cm practical. The 13 feeds of the receiver are placed two beam widths apart on the sky, allowing a 4 pointing tessellation pattern to completely cover an area of the sky  $\sim 1.5^\circ$  across, matching well the typical mid-latitude *EGRET* error box. We have completed a survey of 56 unidentified *EGRET* sources using the Multibeam receiver (Roberts et al. 2004). Each observation was  $\sim 35$  min. long, with a sampling time of 0.125 ms. This is the same integration time as the highly successful Parkes Multibeam Galactic Survey (Kramer et al. 2003) and 8 times that of the Swinburne mid and high-latitude surveys (Edwards et al. 2001, Jacoby et al. 2003). In order to maintain sensitivity to pulsars in even tight binaries, we performed acceleration searches on all of the data using *Presto* (Ransom 2001). The sources were selected using the following criteria:  $|b| > 5^\circ$  (so as not to overlap with the PMB plane survey), no probable blazar counterpart (Mattox, Hartman, Reimer 2001), declination  $< +20^\circ$  so as to be easily accessible to the Parkes telescope, and a 95% confidence error contour which is well covered by the four pointing tessellation pattern.

Initial processing of the data has resulted in the discovery of three new pulsars in binary systems and the redetection of a fourth. A fifth binary pulsar in the surveyed

area discovered in the Swinburne survey (Edwards and Bailes 2001) was not redetected. 5 binary pulsars within the total surveyed area is about twice what would have been expected from a simple extrapolation of numbers detected from previous surveys. Due to the low number, whether this is statistically significant is difficult to say. Since long term timing of these pulsars has only recently commenced, we do not yet know whether any of these new pulsars are energetically capable of producing the  $\gamma$ -ray emission from their coincident *EGRET* sources.

### New Binary Pulsars in *EGRET* Error Boxes

Pulsar	$P$ s	$P_B$ d	D kpc	Ref
PSR J0407+1607	0.0257	669	1.32	Lorimer et al. 2003
PSR J1614–2238	0.00315	8.68	1.27	Current Survey
PSR J1614–2315	0.0335	3.15	1.89	Current Survey
PSR J1744–3924	0.1724	0.19	3.05	Current Survey + PMB
PSR J1745–0952	0.0194	4.94	1.83	Edwards and Bailes 2001 (not detected)

We have also discovered three new isolated pulsars. In addition, we redetected 6 out of 7 previously known pulsars. Again, we do not yet have measured spin-downs for the new pulsars, and none of the previously known pulsars with published period derivatives appear energetically capable of producing  $\gamma$ -rays. We are not certain why we have detected so few isolated, slow pulsars. However, at the sensitivity threshold of this survey, the low-frequency RFI in our data is quite problematic. For slow, low DM pulsars expected from the Gould belt, the pulse dispersion at 20cm is not great enough to distinguish pulsar signals from man-made pulsed signals. While we may be able to extract a few more slow pulsars from this data, it will probably require a longer wavelength survey to have good sensitivity to pulsars in the Gould belt.

### Isolated Pulsars in *EGRET* Survey Error Boxes

Pulsar	$P$ s	$\log \dot{E}$ erg/s	D kpc	Ref
J1632-10	0.7176	-	> 50	Current Survey
J1636-1509	1.1794	-	1.99	ATNF not detected
J1650-1654	1.7496	31.4	1.47	ATNF
J1725-07	0.2399	-	1.69	Current Survey
J1741-2019	3.9045	31.0	1.72	ATNF
J1741-3927	0.5122	32.7	3.21	ATNF
J1800-01	0.7831	-	1.62	Current Survey
J1821+17	1.3667	-	3.26	ATNF
J1832-28	0.1992	-	3.32	ATNF
J1904-1224	0.7508	31.8	3.37	ATNF

## 5. Conclusion

Both large scale radio surveys and deep radio searches targeting X-ray sources have resulted in the discovery of interesting new pulsars coincident with unidentified *EGRET* sources. X-ray and radio imaging of *EGRET* error boxes has also revealed the presence of energetic new pulsars through the emission of associated wind nebulae. Radio pulse searches of other X-ray sources and ultra-deep observations of the currently known PWN are planned or underway. We have also begun a northern extension of our mid-latitude

survey using the GMRT. The goal is to discover and start timing as many potential  $\gamma$ -ray pulsars as possible before the launch of *AGILE*. We also hope to obtain deep, high resolution images of PWN to determine accurate morphologies which can constrain pulsar geometry allowing case by case predictions of what will be seen with the next generation of  $\gamma$ -ray satellites.

Besides detecting pulsations, goals for *AGILE* include confirming  $\gamma$ -ray variability and possibly correlating it with X-ray variations. In addition, every effort should be made to constrain the mid-latitude source error boxes to be within the field of view of imaging X-ray satellites. This will allow counterpart searches to commence before or concurrent with the launch of *GLAST*.

### Acknowledgements

I thank C.-Y. Ng for the sample PWN model image. I also thank Jason Hessels, Cindy Tam, Vicky Kaspi, and Scott Ransom for comments.

### References

- Braje, T.M. et al. : 2002, *Astrophys. J. Lett.* **565**, LL91.
- Camilo, F. et al. : 2001, *Astrophys. J. Lett.* **557**, LL51.
- D'Amico et al. : 2001, *Astrophys. J. Lett.* **552**, LL45.
- Edwards, R.T. et al. : 2001, *Mon. Not. R. Astr. Soc.* **326**, 538.
- Edwards, R.T., Bailes, M. : 2001, *Astrophys. J.* **553**, 801.
- Frail, D.A. et al. : 1996, *Astrophys. J. Lett.* **464**, LL165.
- Grenier, I.A. : 2002, Proc. Texas Symposium, Florence, Italy.
- Halpern, J.P., Holt, S.S. : 1992, *Nature* **357**, 222.
- Halpern, J.P. et al. : 2001, *Astrophys. J. Lett.* **552**, LL125.
- Harding, A.K. et al. : 2003, Proc. 34th COSPAR Sci. Assembly, Symp. on SNR and NS.
- Hester, J.J. et al. : 2002, *Astrophys. J. Lett.* **577**, LL49.
- Hessels et al. : 2003, in preparation
- Jacoby, B.A. : 2003, Radio Pulsars, ASP Conf. Ser. Vol. 302 (Bailes, Nice, Thorsett ed.) P. 133
- Jones, B.B. : 1999, Ph.D. Thesis, Stanford University.
- Kramer, M. et al. : 2003, *Mon. Not. R. Astr. Soc.* **342**, 1299.
- Kuiper et al. : 2000, *Astron. Astrophys.* **359**, 615.
- Lorimer et al. : 2003 in preparation
- McLaughlin et al. : 1996, *Astrophys. J.* **473**, 763.
- Mukherjee, R. et al. : 2000 *Astrophys. J.* **542**, 740.
- Ng, C.-Y., Romani, R.W. : 2003, *Astrophys. J. submitted.*
- Nice,D.J., Sayer, R.W. : 1997, *Astrophys. J.* **476**, 261.
- Nolan, P.L. et al. : 2003, *Astrophys. J. in press.*
- Pavlov, G.G. et al. : 2003 *Astrophys. J.* **591**, 1157.
- Radhakrishnan, V., Cooke, D.J. : 1969, *Astrophys. Lett.* **3**, L225.
- Ransom, S.M. : 2001 PhD. Thesis, Harvard University
- Roberts, M.S.E. et al. : 1999, *Astrophys. J.* **515**, 712.
- Roberts, M.S.E., Romani, R.W., Kawai, N. : 2001 *Astrophys. J. Suppl.* **133**, 451.
- Roberts, M.S.E. et al. : 2002, *Astrophys. J. Lett.* **577**, LL19.
- Roberts, M.S.E. et al. : 2003, *Astrophys. J.* **588**, 992.
- Roberts, M.S.E. et al. : 2004, Young Neutron Stars and Their Environments, IAU Symp. Vol. 218 (Camilo, Gaensler ed.)
- Romani, R.W. : 2001 The Nature of Unidentified Galactic Gamma-Ray Sources, ASSL Vol. 267 (Carraminana, Reimer, Thompson ed.), p. 153